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On Developing a Spectroscopic System for Fast Gas Temperature Measurements in Combustion Environments

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On Developing a Spectroscopic System for Fast Gas Temperature Measurements in Combustion Environments

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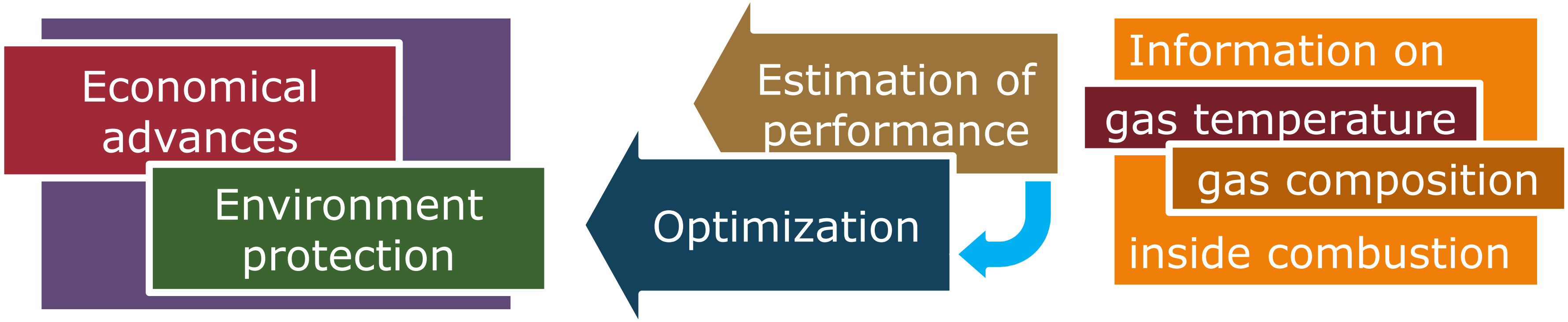


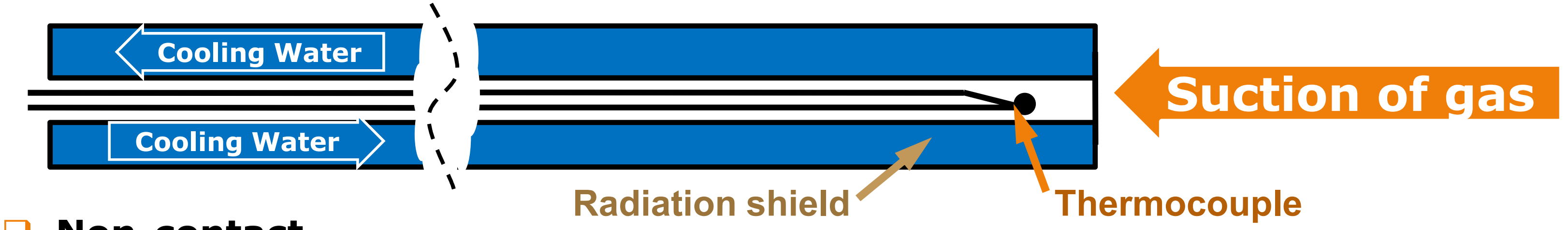
- **Development of methods and equipment for on-line optical measurements of gas temperature and species concentrations**
  - such as O_2, NO_x, SO_2, CO, CO_2, H_2O and C_xH_y
  - in flames or hot gas flows
  - inside boilers, exhaust pipes, engines, etc.
  - using IR/UV emission/absorption spectrum measurements
- **Investigation of spectral properties of gases at high temperatures**
  - This allows to improve quality of spectrum modeling and thus to increase accuracy of on-line measurements
- **Calibration of temperature and infrared measuring equipment (accredited by DANAK)**

Outline

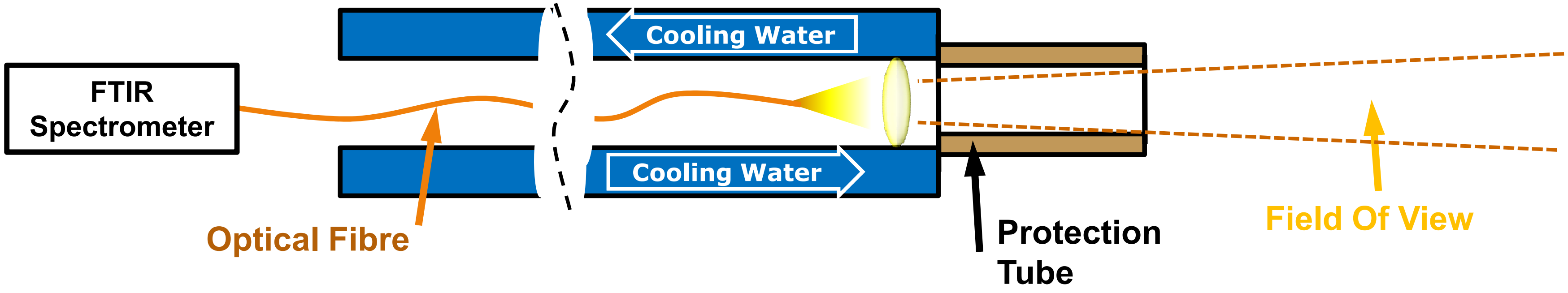
- **Fast gas temperature measurement**
- **Existing techniques for gas temperature measurement**
- **Development of a new technique for fast gas temperature measurement**
  - Schematic
  - Model
  - Calibration
  - Validation
- **Application on an industrial boiler**
  - Fast spectral measurements inside the boiler
  - Temperature calculation results
    - Temperature variations with high temporal resolution
- **Further development of the system**
  - Multichannel spectrometer
  - 2D Tomography

Existing Techniques

- **High temporal resolution is necessary for combustion diagnostics**
  - At least 1 kHz is needed in order to resolve temperature variations which occur e.g. due to turbulent fluctuations
- **Contact**
  - Suction pyrometers: typical response time 15–60 s

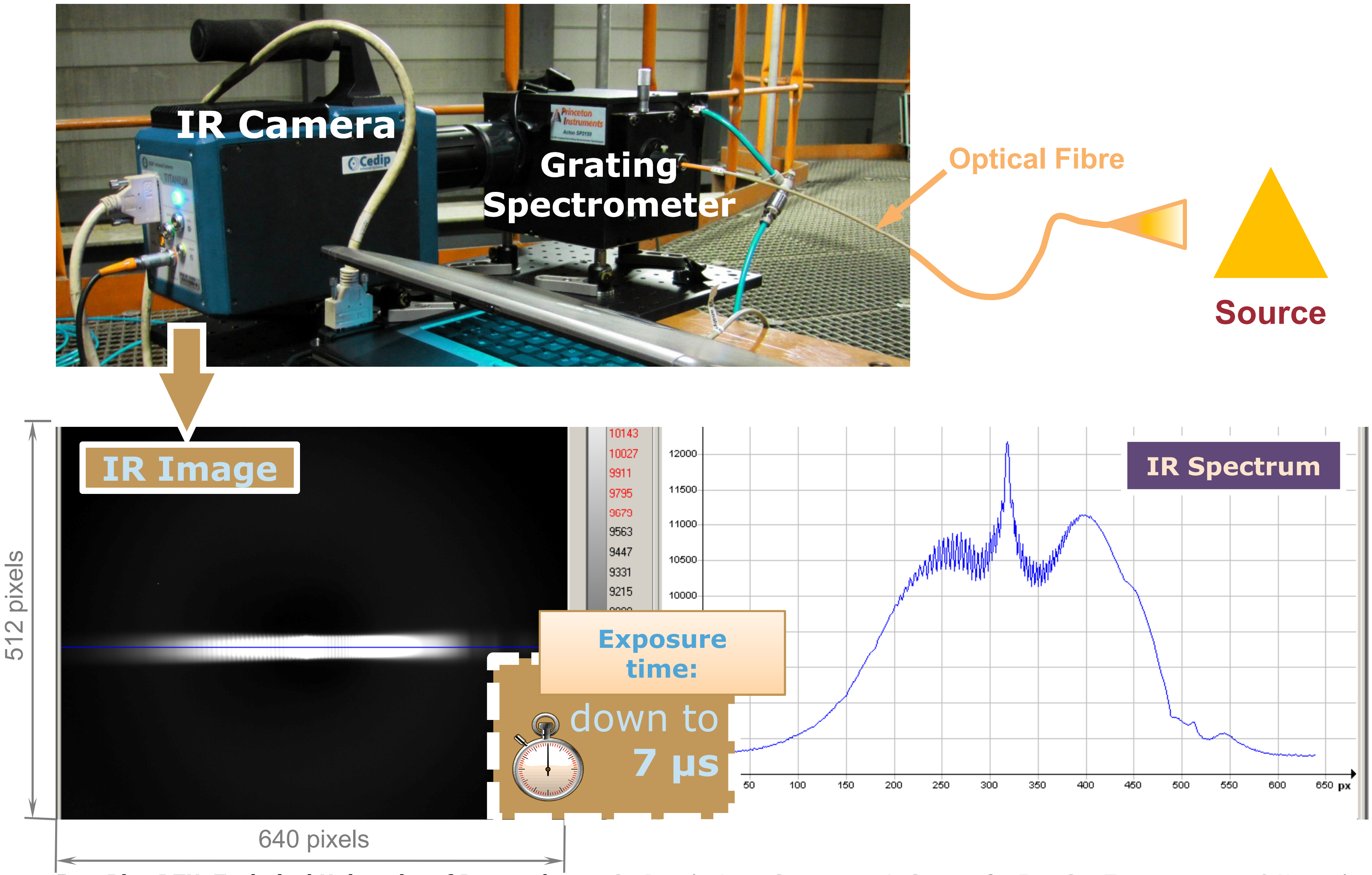


- **Non-contact**
  - FTIR: has been successfully applied for *in situ* non-contact gas analysis in industrial combustors, typical temporal resolution 2 Hz



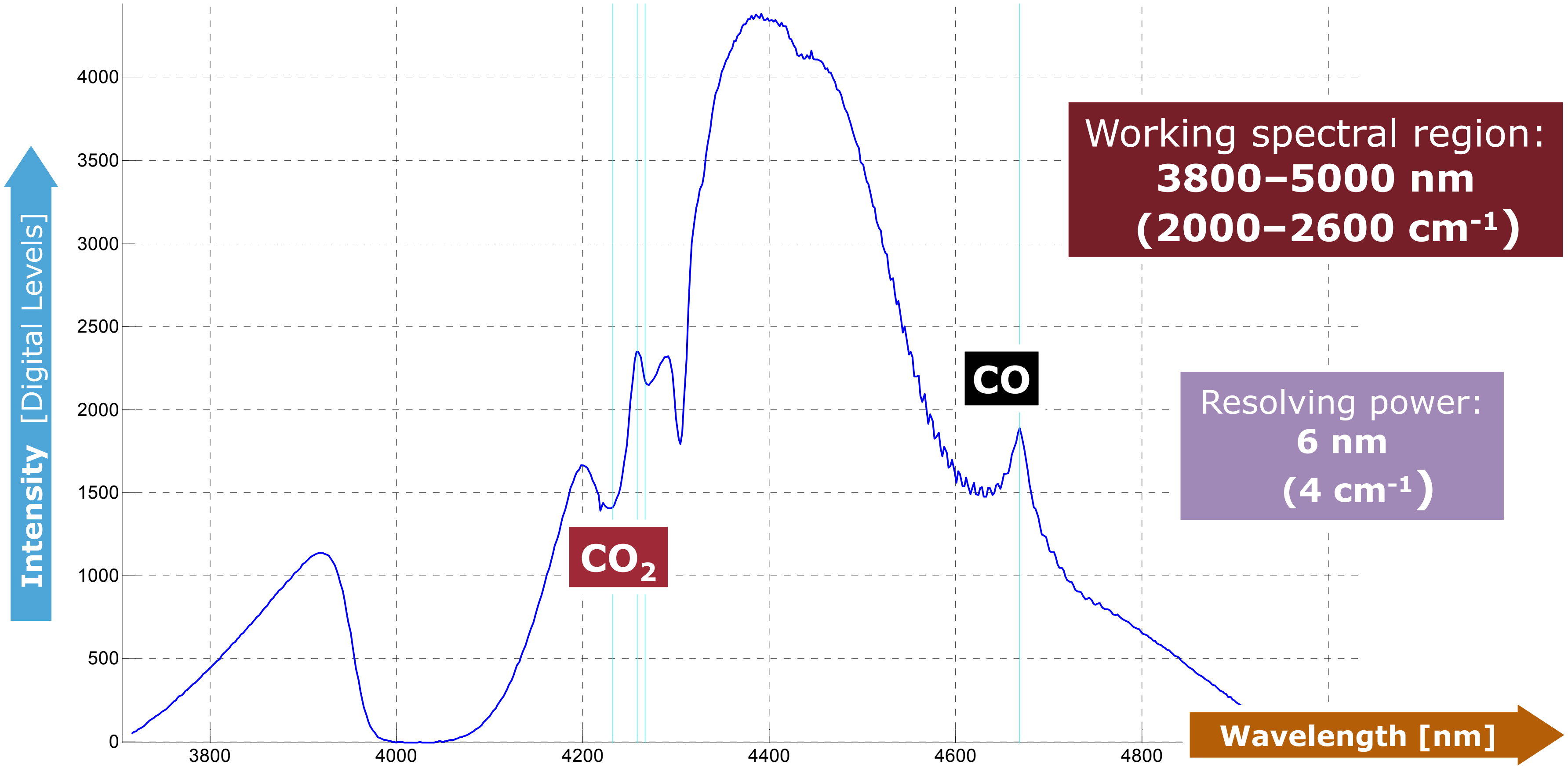
  - CARS: very high temporal and spatial resolution, complicated setup

A New System


IR Camera
Grating Spectrometer
Optical Fibre
Source
IR Image
512 pixels
640 pixels
Exposure time:
down to
7 µs
IR Spectrum
10143
10027
9911
9795
9679
9563
9447
9331
9215
12000
11500
11000
10500
10000
50
100
150
200
250
300
350
400
450
500
550
600
650 px

Wavelength Calibration

- What is the correspondence between pixel numbers along the horizontal axis in the IR image and wavelengths?
- CO and CO_2 lines are used



Mathematical Model

$$S(\lambda) = R(\lambda)\, L(\lambda, T) + B(\lambda)$$

- **A static model of the spectral measurement:**
  - ***S* (λ)** – a received signal from a source [digital levels]
  - ***L* (λ,*T*)** – unknown spectral radiance of the source [W / m^2 sr m]
  - ***R* (λ)** – a response (or instrument) function
  - ***B* (λ)** – constant background radiation

$$R = \frac{S_2 - S_1}{L^{BB}(T_2) - L^{BB}(T_1)}$$

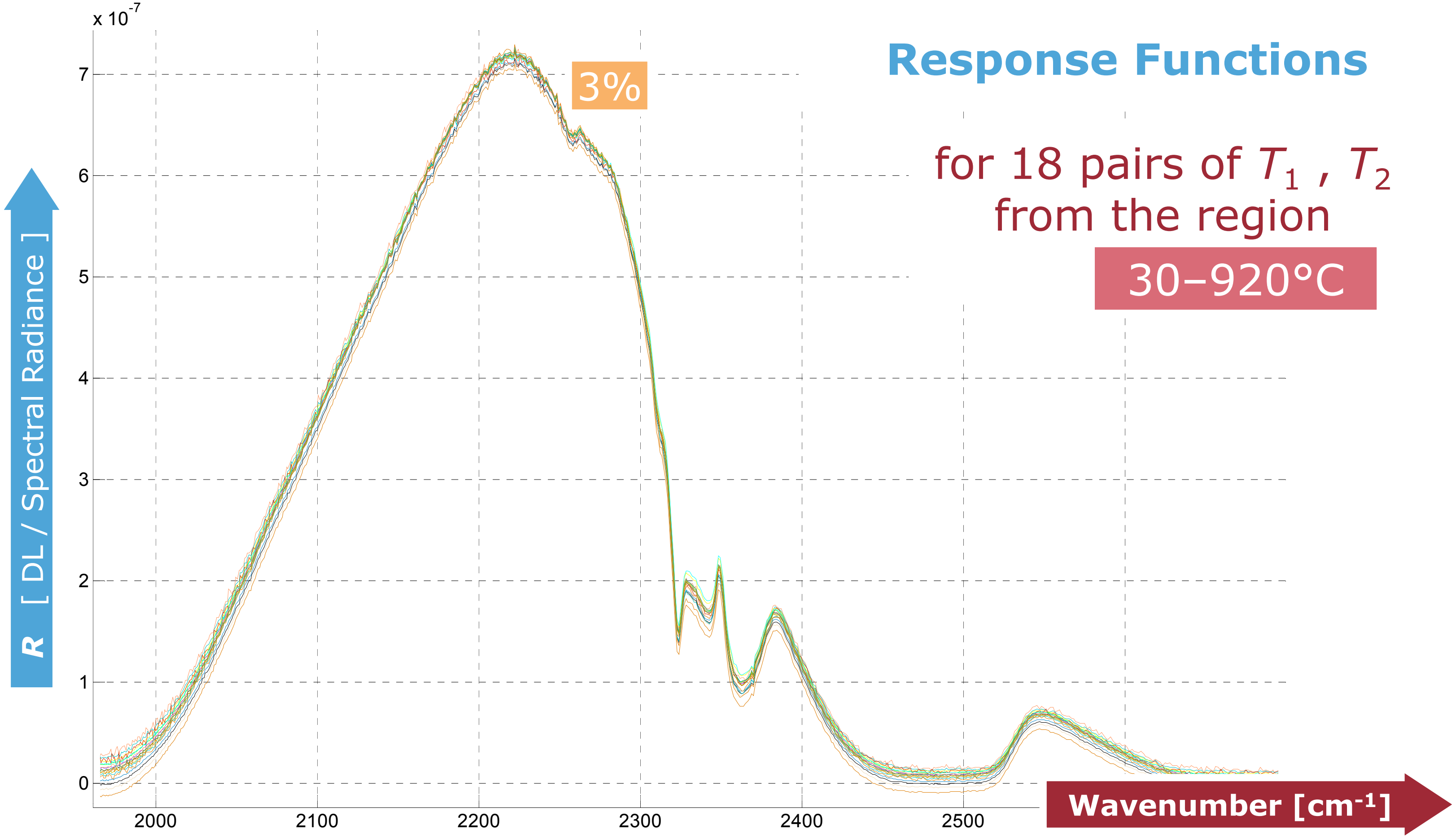
- **Calibration of Intensities Scale** (reference sources having known spectral radiance *L* are used)
  - **S_1 , S_2** – received signals for a black body at temperatures T_1 , T_2
  - **L^{BB} (T_1), L^{BB} (T_2)** – spectral radiance of the black body calculated from the Planck Law

$$L = \frac{S\left(L_2^{BB} - L_1^{BB}\right) + S_2 L_1^{BB} - S_1 L_2^{BB}}{S_2 - S_1}$$

- The unknown spectral radiance of the source is calculated using reference data

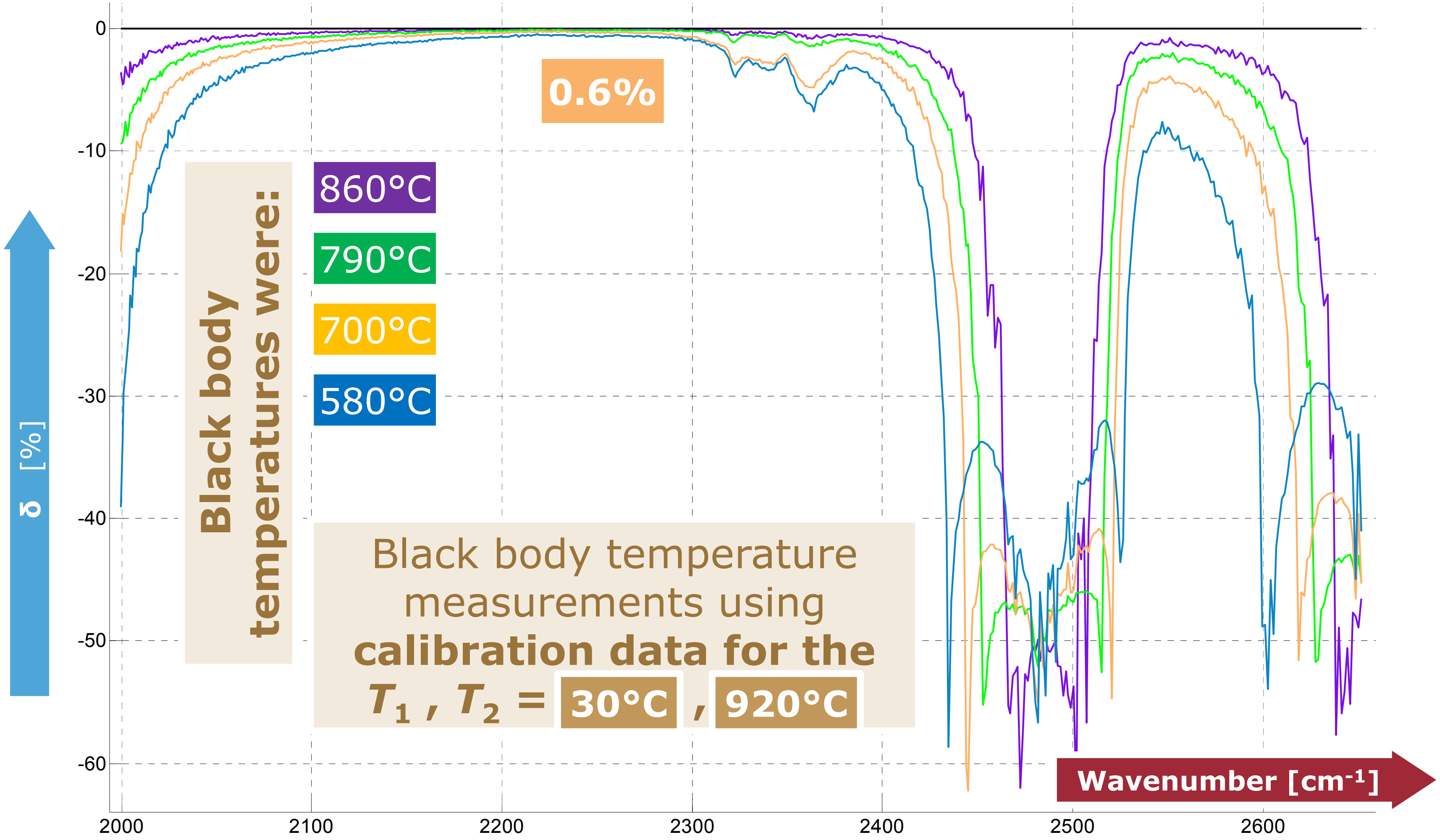
Intensity Calibration

- Variations (%) of the response function R for different pairs of reference source temperatures T_1 , T_2



Validation

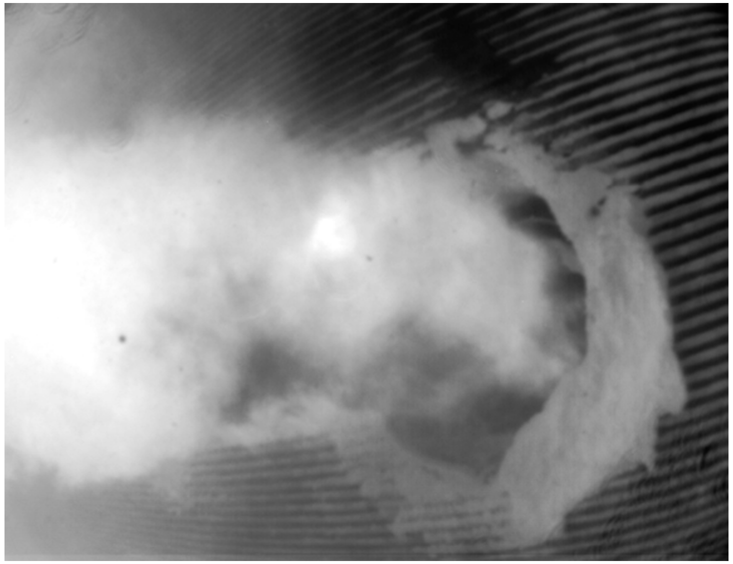
- Relative error δ (%) of reference source temperature measurement



Industrial Boiler

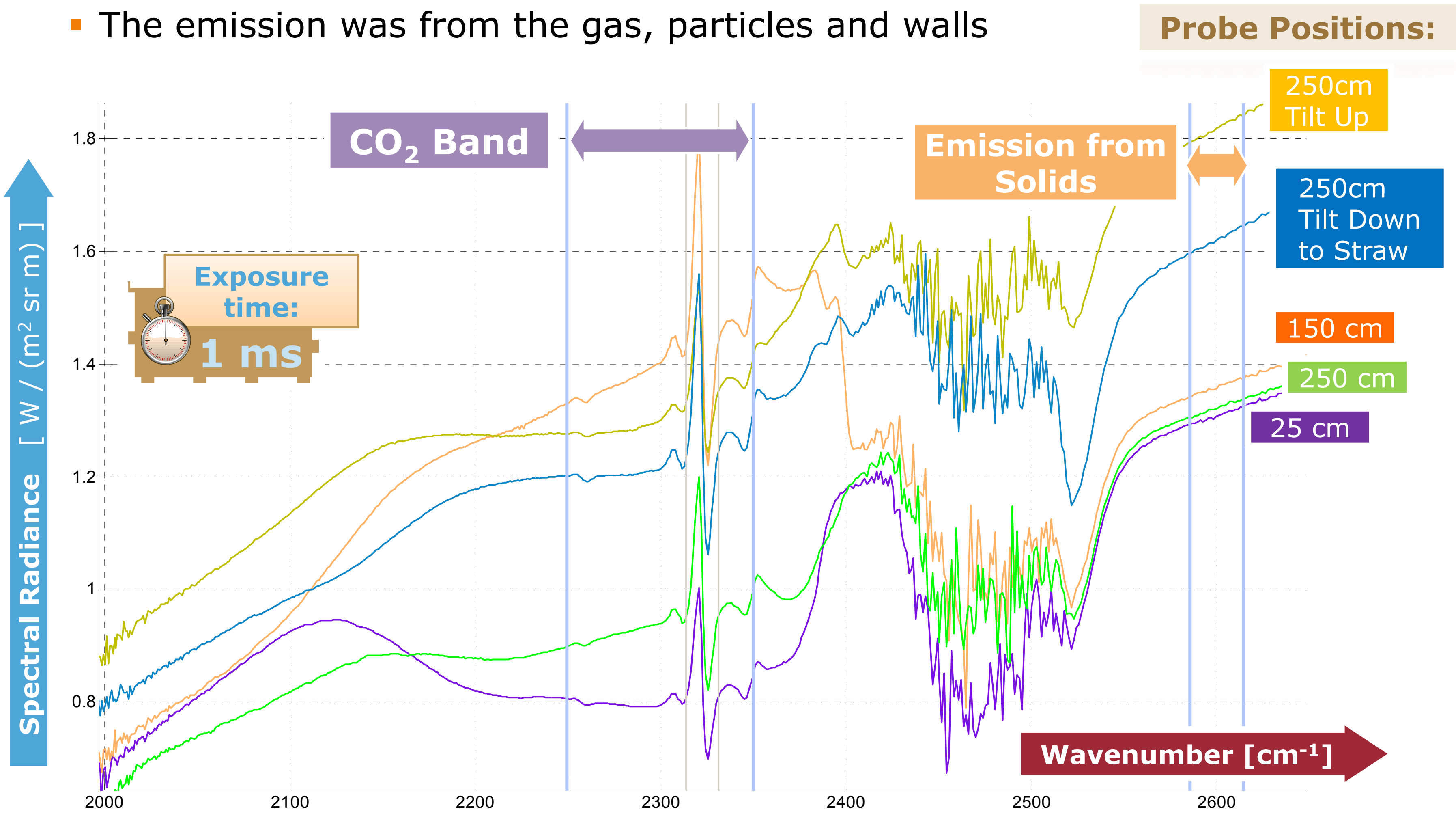
- A boiler of a biomass-coal power station

- Thermal picture of the 40 MW flame



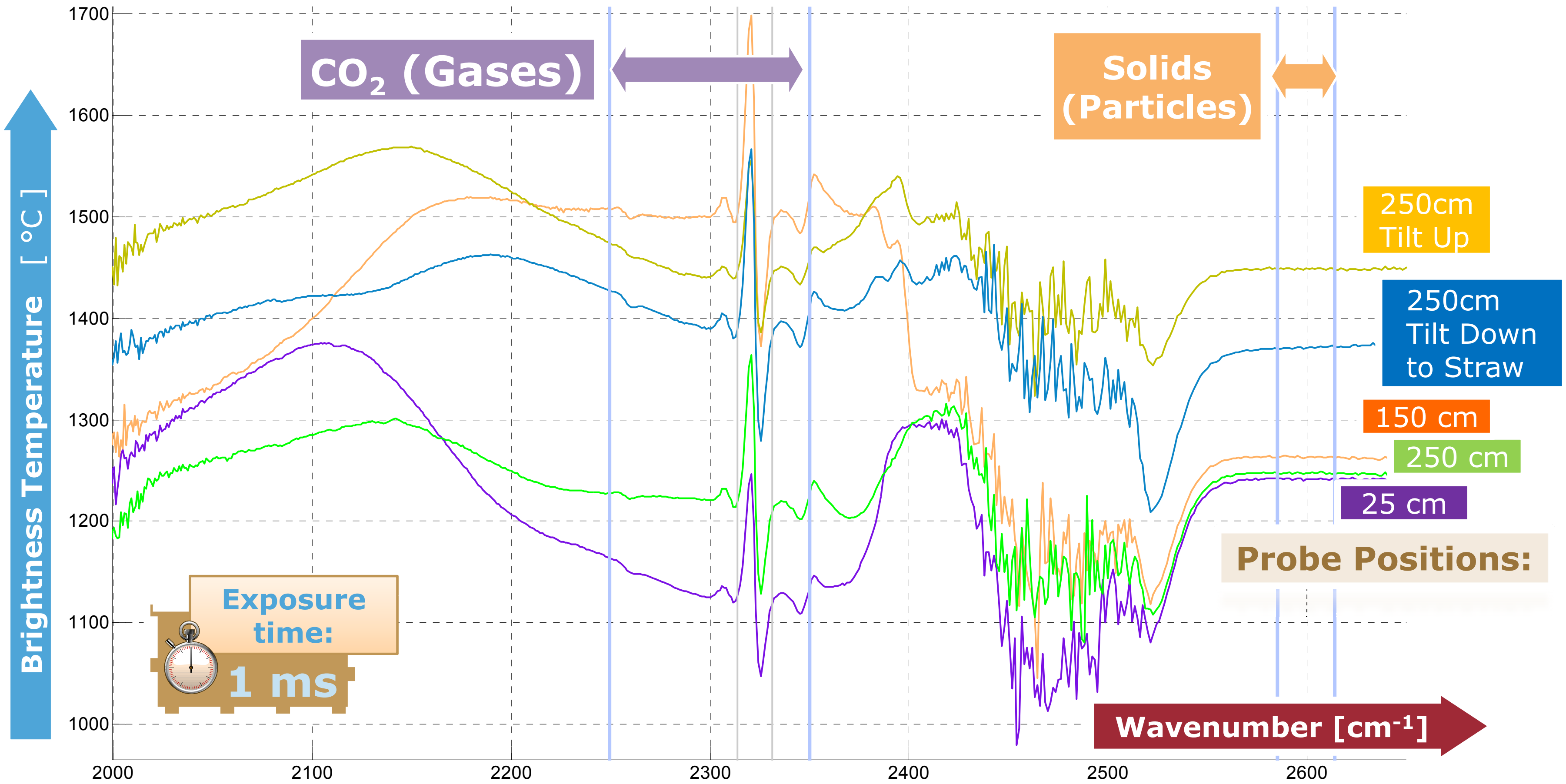
Spectra

- **Emission spectra for several insertion depths of the probe**
  - The emission was from the gas, particles and walls



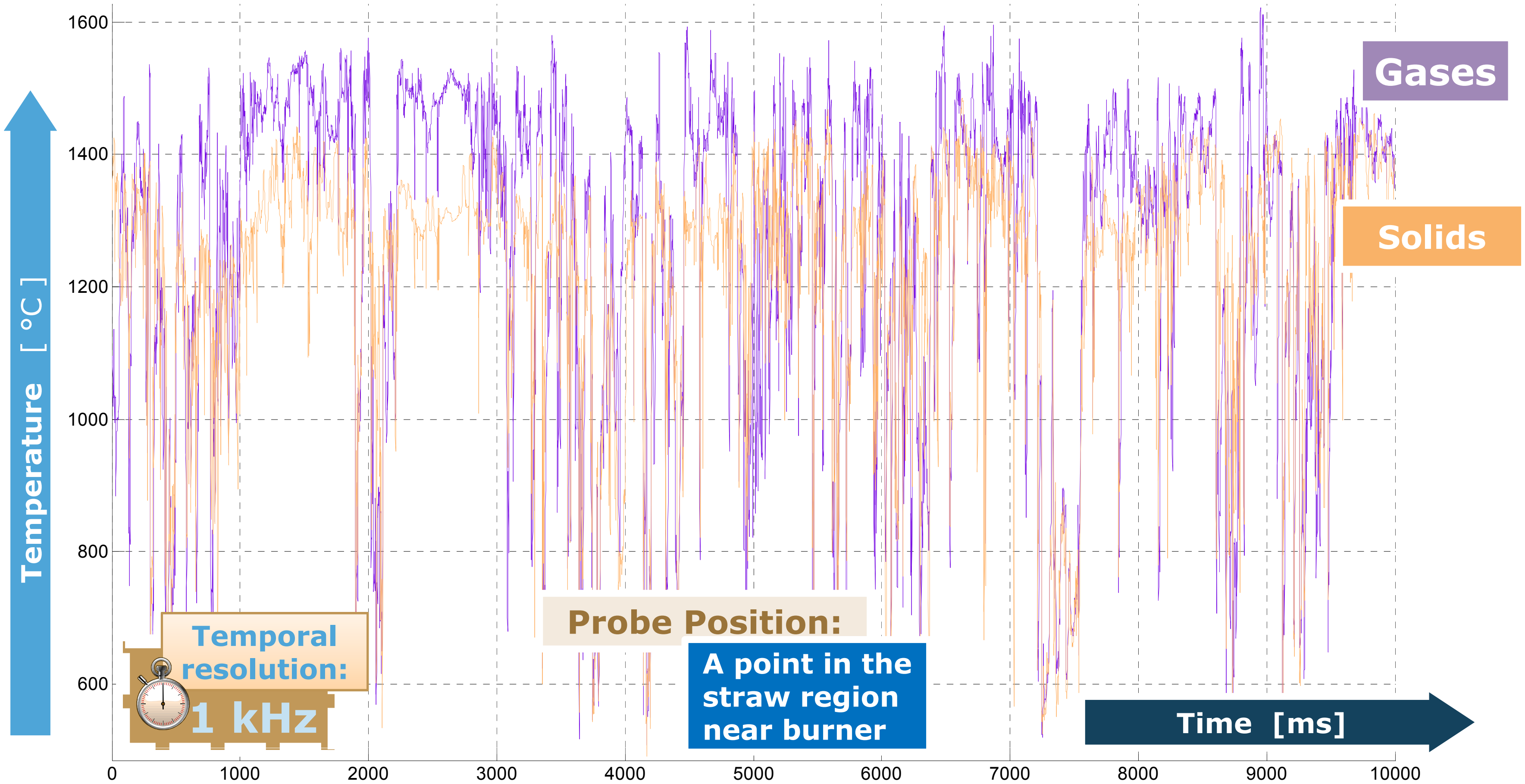
Brightness Temperature

- Brightness temperature is calculated from the Planck Law for each spectral point in each spectrum



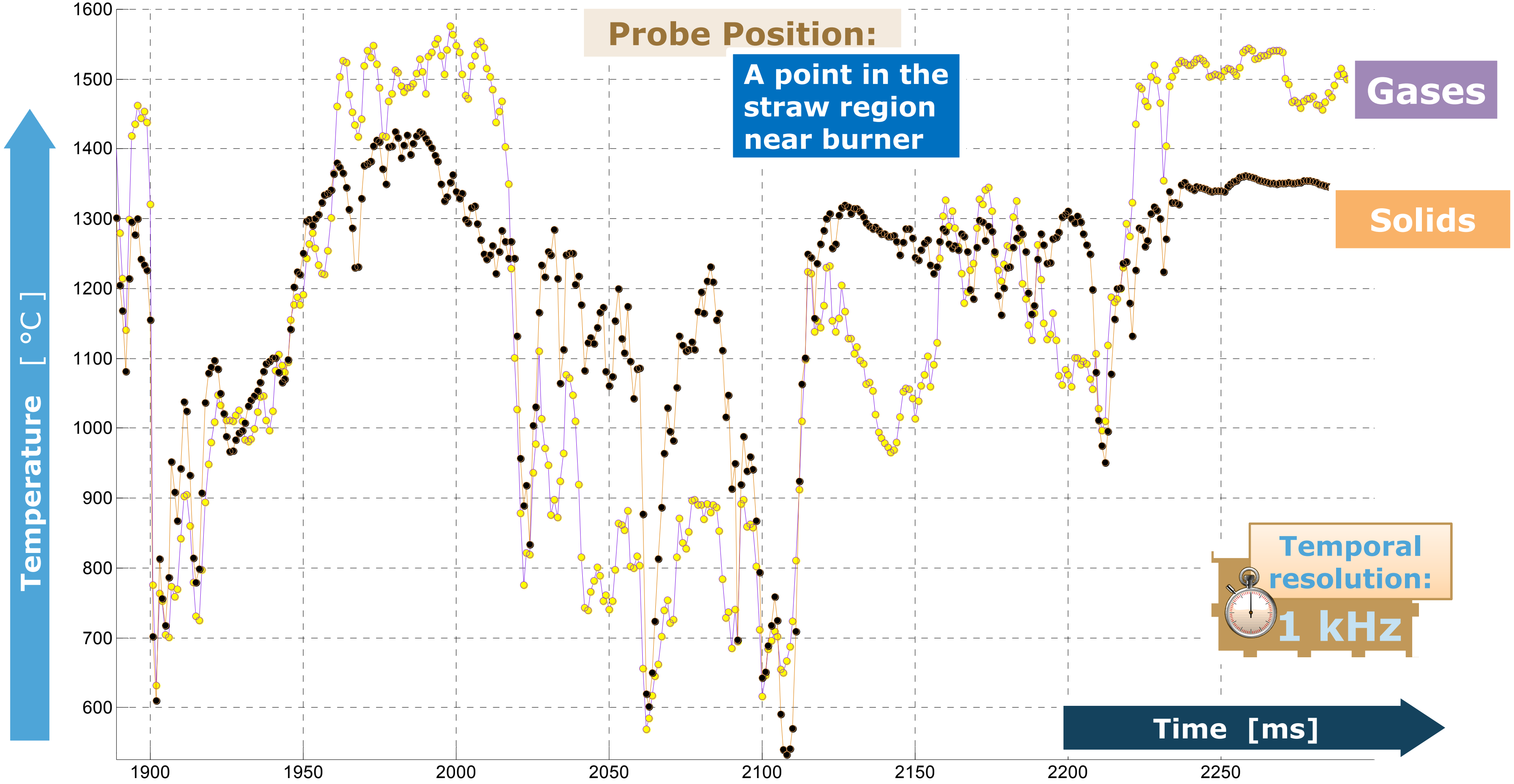
Temperature Variations: Straw Region near Burner

- Temperature is averaged throughout each band (CO_2 and solids) in each spectrum taken at each time point and plotted versus time



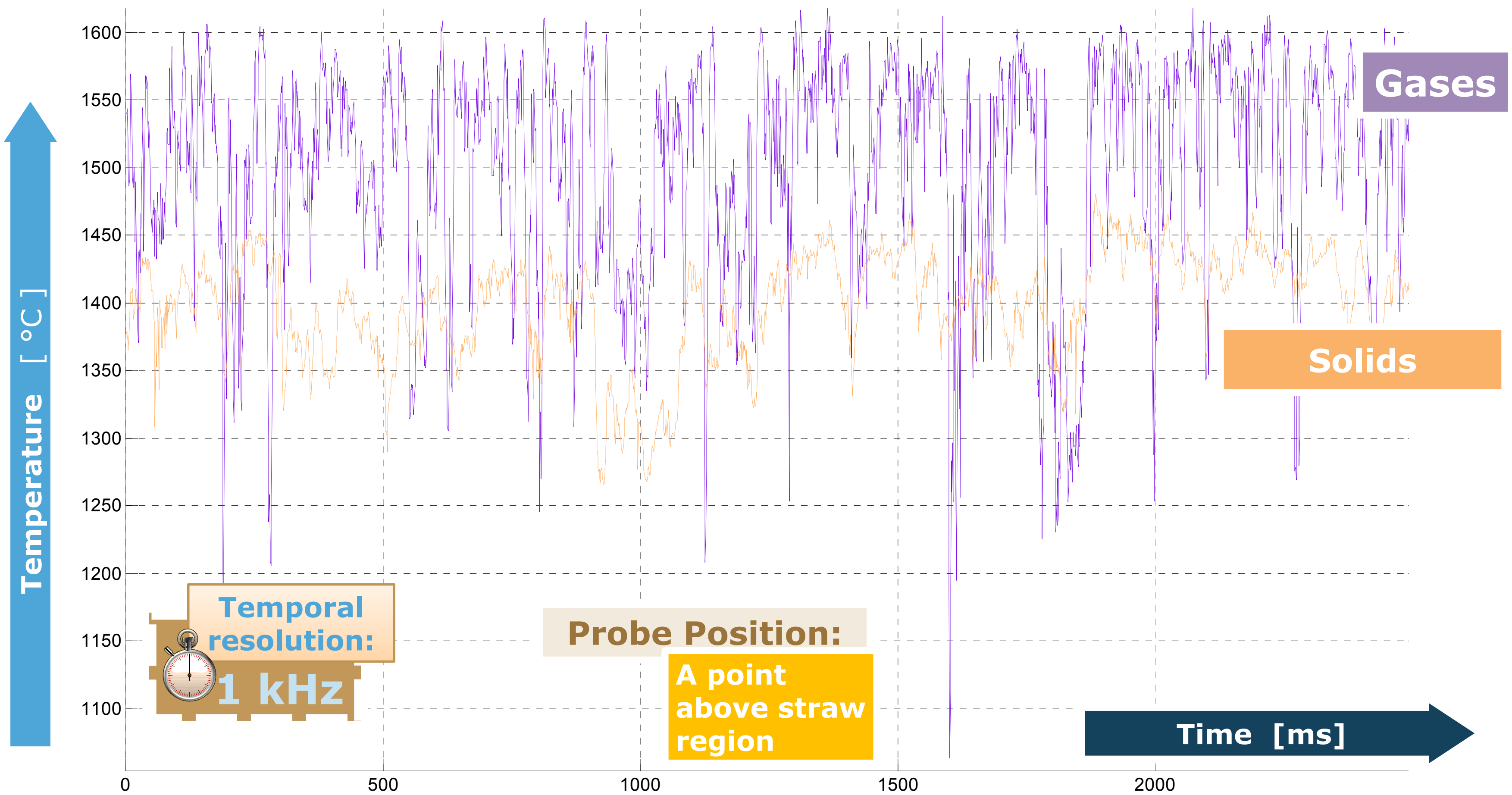
Temperature Variations: Straw Region near Burner

- **Zoom In:** 1kHz is enough to resolve temperature variations which occur due to turbulent fluctuations



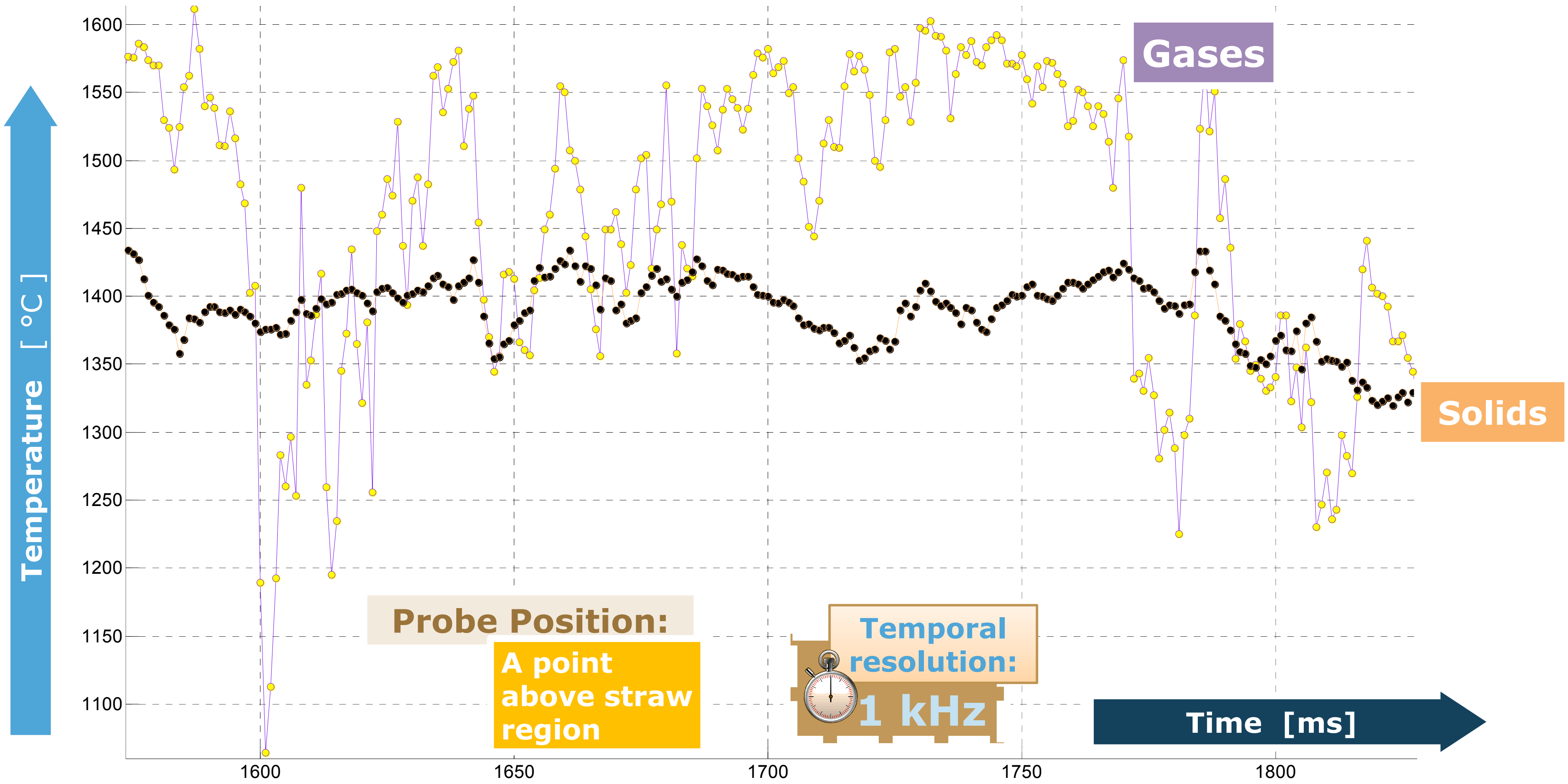
Temperature Variations: Above the Straw Region

- Here gas temperature is higher than that of particles. Most of heat is already released at this point, and hence gas is hotter than particles



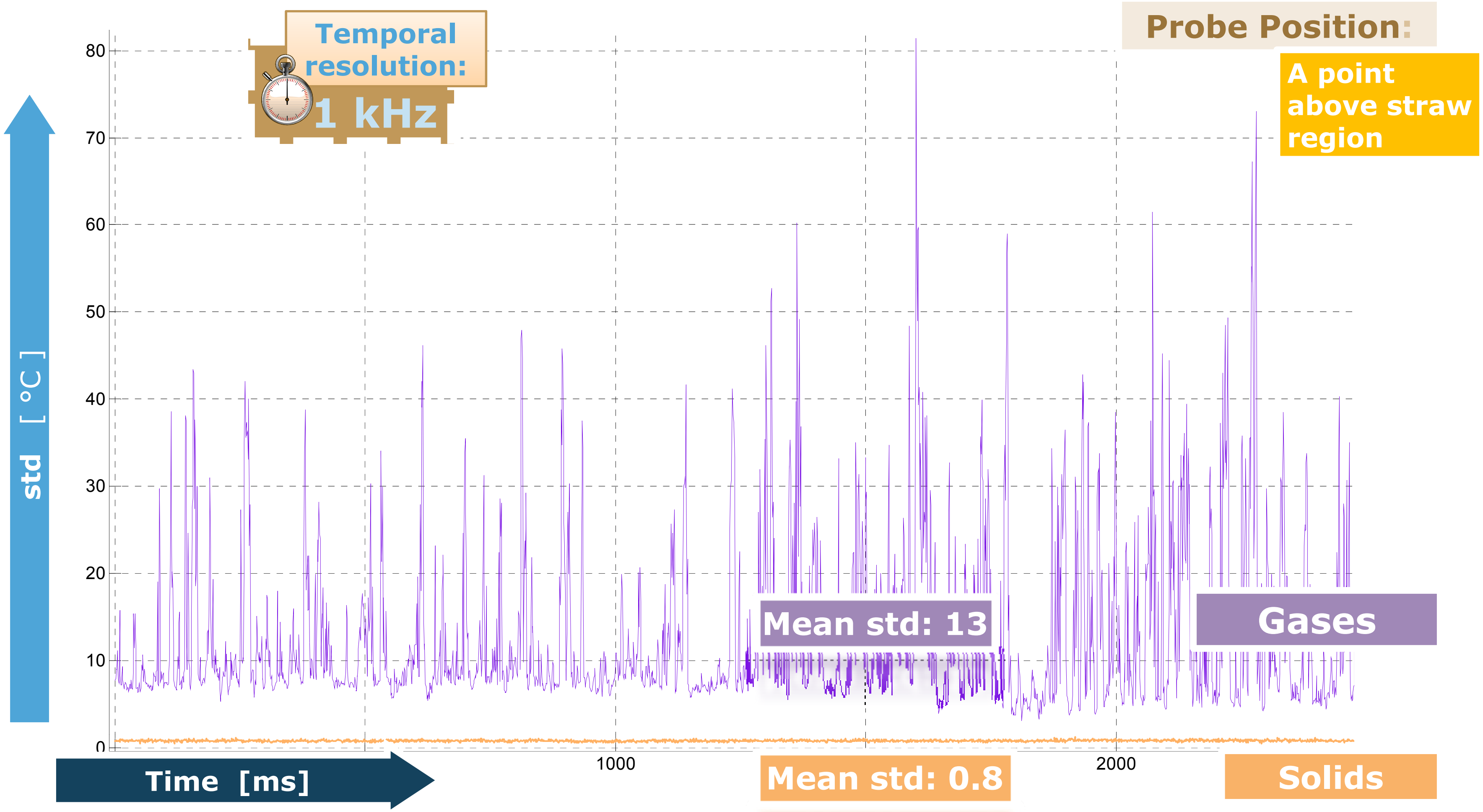
Temperature Variations: Above the Straw Region

- **Zoom In:** Particles (solids) do not undergo as huge temperature variations as gases do



std of temperature values

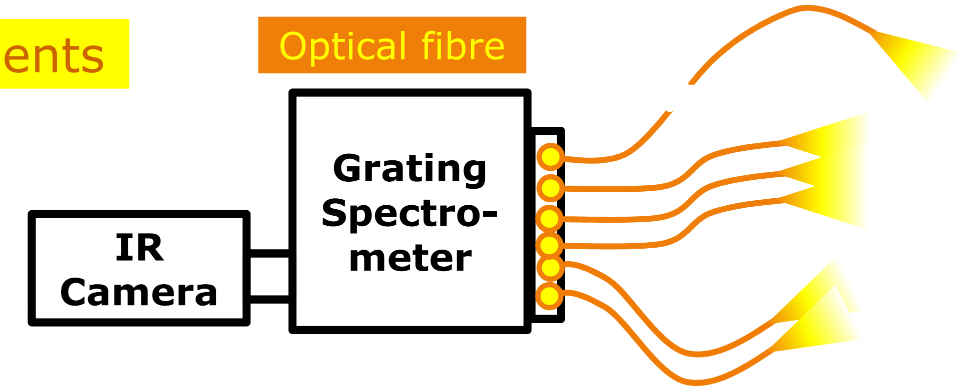
- How do temperature values deviate throughout each band in each spectrum?

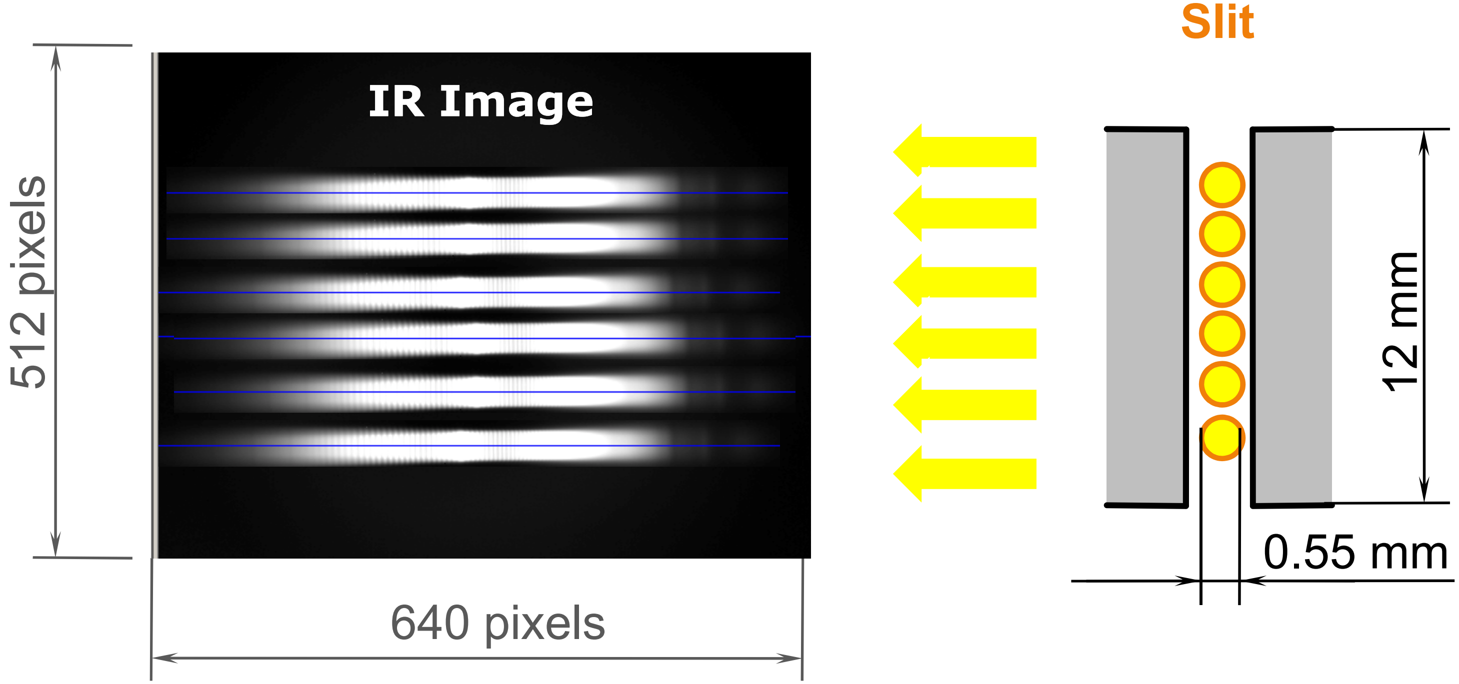


Further development:
Multichannel Spectrometer

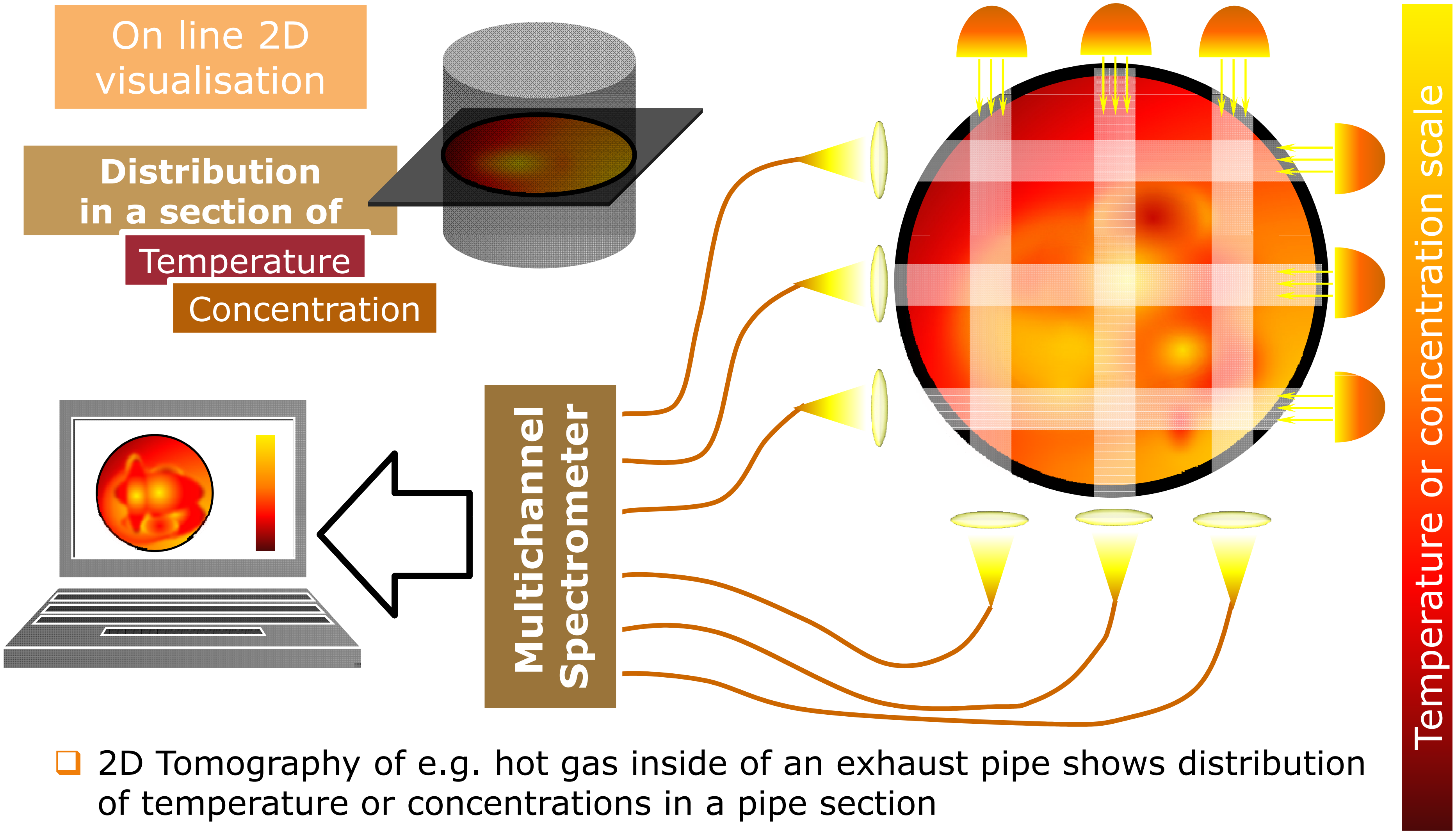
Simultaneous spectral measurements

- A multichannel assembly allows to perform spectral measurements simultaneously from several positions





Further development:
2D Tomography



- 2D Tomography of e.g. hot gas inside of an exhaust pipe shows distribution of temperature or concentrations in a pipe section

Conclusion

- A system for fast gas temperature measurements for use on industrial scale has been developed
  - Grating spectrometer + IR Camera
  - Maximum possible temporal resolution 142 kHz

- The system has been calibrated and validated

- It has been successfully applied on an industrial boiler
  - Spectral measurements has been taken
    - at several points inside the boiler
    - with temporal resolution of 1 kHz
  - Temperature has been calculated for gases and solids
    - 1 kHz is high enough to resolve temperature fluctuations which occur due to turbulence
  - Reliability of results has been estimated

- The system provides flexibility and is promising in further developments
  - Simultaneous spectral measurements
  - 2D Tomography of combustion gases